N91-32630

LIGHTNING PROTECTION FOR SHUTTLE PROPULSION ELEMENTS

Carolyn C. Goodloe
Systems Analysis And Integration Laboratory, EL-56
NASA/Marshall Space Flight Center
Huntsville, Alabama 35812
and
Robert J. Giudici
Sverdrup Technology, Inc.
620 Discovery Drive
Huntsville, Alabama 35806

ABSTRACT

The results of lightning protection analyses and tests are weighed against the present set of waivers to the NASA lightning protection specification. The significant analyses and tests are contrasted with the release of a new and more realistic lightning protection specification, in September 1990, that resulted in an inordinate number of waivers. After the first decade of Shuttle flight the Shuttle remains vulnerable to the effects of lightning. A variety of lightning protection analyses and tests of the Shuttle propulsion elements, the Solid Rocket Booster, the External Tank, and the Space Shuttle Main Engine, have been conducted. These tests range from the sensitivity of solid propellant during shipping to penetration of cryogenic tanks during flight.

The Shuttle propulsion elements have the capability to survive certain levels of lightning strikes at certain times during transportation, launch site operations and flight. Changes are being evaluated that may improve the odds of withstanding a major lightning strike. The Solid Rocket Booster is the most likely propulsion element to survive if systems tunnel bond straps are improved. An initial decision not to harden the Space Shuttle Main Engine to lightning has been reversed. Wiring improvements have already been incorporated and major lightning protection tests have been conducted. The External Tank remains vulnerable to burn-through penetration of its skin. Proposed design improvements include the use of a composite nose cone and conductive or laminated thermal protection system coatings.

INTRODUCTION

Lightning protection concerns and the resulting analyses, tests, design changes or waivers for the Shuttle propulsion elements are summarized from the perspective of the Systems Analysis And Integration Laboratory of the Marshall Space Flight Center (MSFC). Shuttle propulsion elements are the responsibility of MSFC and are differentiated from the Shuttle Orbiter which is the responsibility of the Johnson Space Center (JSC). There are three major Shuttle propulsion elements: (1) Solid Rocket Booster, (2) External Tank and (3) Space Shuttle Main Engine. The relationship of the Shuttle propulsion elements and the Shuttle Orbiter to the overall Space Shuttle is depicted in Fig.1.

All Space Shuttle elements, and the Kennedy Space Center (KSC) launch site, share a common lightning protection specification: NSTS 07636, Revision E. This revision was released in September 1990. The specification subdivides lightning characteristics to simulate the aspects of a major lightning strike: there is an initial component A, (200 kA peak, 500 μs); an intermediate component B, (4.2 kA peak, 10 coulombs); and a continuing component C, (400 A, 200 coulombs). Other lightning components defined by the specification account for restrikes and multiple bursts. Test equipment has been devised to simulate the various aspects of lightning protection.

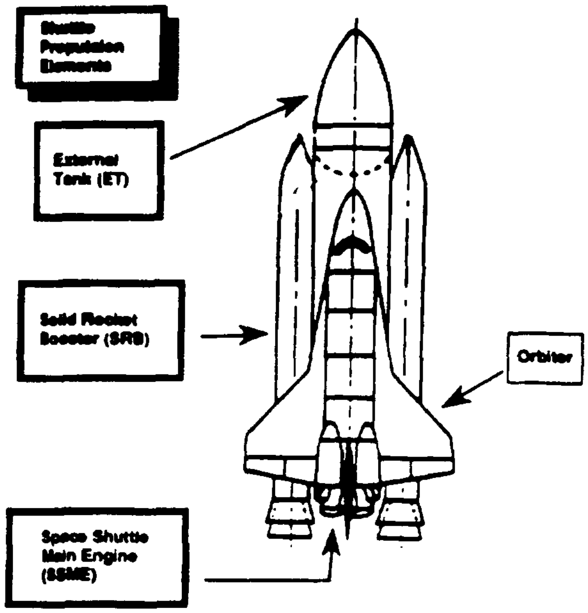


Figure 1. Shuttle Propulsion Elements

EXTERNAL TANK

The External Tank (ET) is an aluminum vessel, 47 m (154 ft) in length and 8.4 m (28 ft) in diameter. A diagram identifying the major components is shown in Fig.2. Two Solid Rocket Boosters and the Orbiter are attached. The thickness of the 2219 aluminum skin varies from 2 to 3.6 mm (80 to 140 mils). Insulation, 1.9 to 3.8 cm (0.75 to 1.5 inches) thick, is required to minimize cryogenic boil-off and to provide protection against aerodynamic heating. The Tank has three main components: the Liquid Oxygen (LO2) tank, located under the forward ojive; the intertank section; and the aft liquid hydrogen (LH2) tank. External cable trays enclose fluid lines, pressurization gas lines, linear shaped charges, and electrical cables. Avionics are located in the nose cone and intertank areas.

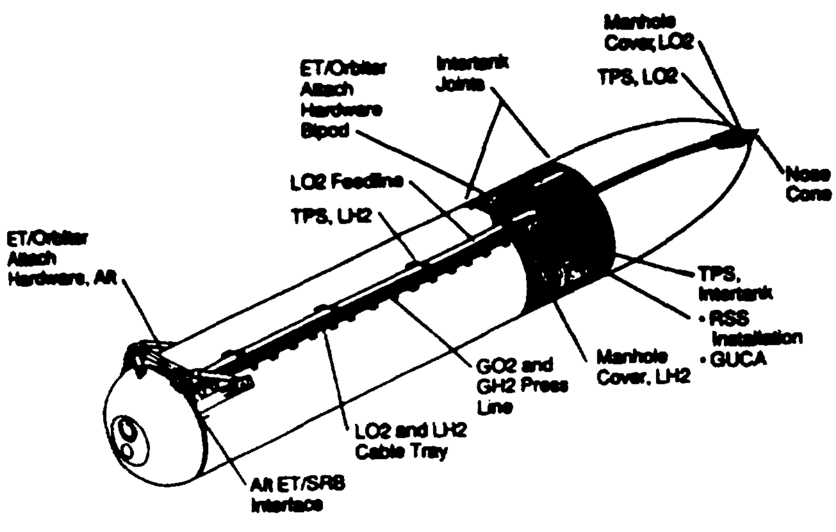


Figure 2. External Tank

External Tank Concerns

Burn-through of the External Tank is one of the most serious lightning threats to the Shuttle propulsion elements because the external tanks are prone to penetration of the skin that could result in hydrogen ignition or oxygen burning or loss of pressurization. During ascent of the Space Shuttle the External Tank is a potential attach point for lightning. The External Tank is protected by a catenary wire system while on the launch pad and is protected against launch into severe weather by strict launch commit criteria. However, there remains a possibility that prediction of triggered lightning strokes during boost may be beyond the capability of completely reliable weather prediction and therefore analyses, tests, and design changes continue with the objective of improving compliance with the lightning protection specification.

The External Tank can probably withstand a lightning strike to the lightning rod located at the forward most tip of the tank nose cone. The rod also functions aerodynamically to reduce thermal protection requirements. Tests [1] on a production nose cone demonstrated the capability of the lightning rod to distribute full lightning currents into the nose cone with no discernible damage. Analysis and tests verify that there would be no damage to the LO2 tank, the intertank, or the LH2 tank resulting from a lightning strike to the lightning rod.

Lightning can strike at any altitude but it is most likely to trigger a lightning strike at altitudes above 460 m (1500 ft). The lightning protection specification applies to a worst case major lightning strike. Practical considerations, though difficult to substantiate, suggest that the External Tank may realistically

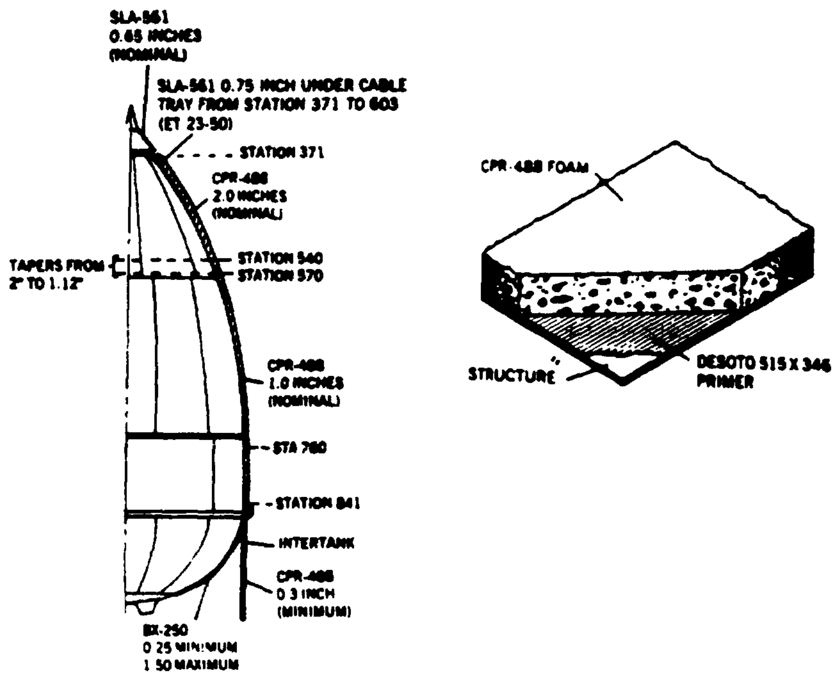


Figure 3. Typical Cross Section of the TPS

encounter less severe lightning strikes. When a lightning strike uses a moving space vehicle as part of its path from a cloud to ground or to another cloud, it establishes a step leader path for the first return stroke and return stroke currents usually continue for several milliseconds. If the whole surface is conductive, the attach point moves back in relatively smooth motion due to the forward motion of the vehicle, but if the surface is covered with insulation the lightning arcs through the insulation and attaches to the aluminum skin at one point. The initial lightning attach point clings to one spot and the

lightning channel bends along the insulated surface forming a heal just above the surface of the insulation. The lightning channel attaches to a new point further along the length of the vehicle when the heal is close enough and the voltage is high enough to arc through the insulation. Before this occurs, the dwell time at the initial attach point may be sufficient to burn through the underlying aluminum skin of the LO2 and LH2 tanks. Details of the flight vehicle insulation are shown in Fig.3.

Commercial aircraft typically survive two lightning strikes per year. The Saturn V, Apollo 12, mission survived two strikes during launch and went on to the second successful Lunar landing. The conductive skin of aircraft and the Saturn vehicle sweep the lightning channel along the surface without penetrating the skin whereas the insulated surface of the External Tank not only increases the dwell time but tends to narrowly focus the arc and enhance the potential to penetrate the walls.

The charge imparted to the skin of a vehicle by a swept stroke is the product of amperes and dwell time. Dwell time is highly dependant on insulation breakdown characteristics and is difficult to predict. There is a minimal data base on the effects of a swept strokes on thickly insulated surfaces, and testing is expensive and difficult to conduct. However, the charge imparted to the skin of the External Tank from a swept stroke can be less than the specified 200 coulomb level for a standing vehicle. Although amount of charge from a swept stroke may not be known, the amount of charge necessary to penetrate the skin of the External Tank can be determined through test and analysis.

A number of tests have been conducted to evaluate tank puncture and the effects of thick insulation. For example, elaborate coupon testing was performed using aluminum coupons covered with thermal insulation and stressed to flight pressures of 34,475 N/m^2 to 275,800 N/m^2 (5 to 40 psi) and liquid nitrogen (LN2) temperatures. A 2.5 mm (100 mil) panel marginally survived 31 coulombs. A 3.6 mm (140 mil) panel punctured but a 4 mm (160 mil) panel survived at a 75 coulomb level [2].

Designs for improving the capability to survive a server lightning strike are being evaluated. Overlaying the thermal protection insulation with laminated layers of thin aluminum and non-conductive adhesive, similar to the Solid Rocket Booster rail car covers, may offer solutions. An 2 mm (80 mil) panel covered with 6.4 mm (2.5 mil) aluminum tape and adhesive withstood 75 coulombs [2]. A normally nonconductive insulated panel required twice this thickness to withstand the same charge level. The outer foil separates from the surface being protected, probably due to the escaping adhesive gasses, and diverts the lightning arc. Painting the insulation with copper impregnated paint has also shown considerable promise and the incorporation of a composite nose cone is under consideration.

Launch Site Protection

The launch pad lightning protection system consists of three major systems: (1) a catenary wire instrumentation system that measures lightning wave form and peak current, (2) a system that measures induced voltage and current flow in the vehicle and ground support equipment, and (3) an optical system that determines the lightning attach point.

An updating of the ground based field mill network is scheduled to be operational by the summer of 1991. This system consists of 37 field mills covering all launch sites at the KSC. Data will be automatically collected in a central data facility.

External Tank Status

The LO2 and LH2 gas pressurization lines are important planned lightning attach points. The LO2 line runs the length of the vehicle and both lines are uninsulated. Lightning can sweep along the uninsulated lines when the vehicle is moving without dwelling long enough to burn through. The lines

have the capability of surviving a swept stroke when vehicle velocity is above 20 m/s (64 fps). A waiver is in effect because the pressurization lines will puncture if the vehicle is stationary.

The cable trays were verified to withstand the direct effects of a 25 kA lightning strike derived from an earlier release of the lightning protection specification. The Rev E specification calls for 200 kA. Analyses of indirect effects, the coupling of undesired current and voltage into electrical cable harnesses from nearby structure or fluid and gas lines, must likewise be upgraded to the 200 kA level.

The major waivers to the External Tank involve tank penetration inclusive of the nose cone, LO2 tank, LH2 tank, and aft dome of the LH2 tank. A number of analyses and tests have been requested. One test, to evaluate the effects of a lightning strike to a simulated insulated liquid oxygen tank, may be performed at MSFC Huntsville in early 1991.

SPACE SHUTTLE MAIN ENGINE

The engine using the cryogenics from the External Tank is located in the Orbiter. The Space Shuttle Main Engine (SSME) is actually three engines having an engine controller mounted to each engine. The controllers contain digital computers necessary to process sensor signals, and issue control signals to hydraulic actuators and igniters. The existing controller is referred to as Block I but this version is scheduled to be replaced by a Block II controller in 1992. The controllers are wired to engine components and to Orbiter interface wiring. Features of the engine are shown in Fig.4. Note that the main engine is largely protected within the Orbiter boat tail but there remains concerns for cable shielding of the Block II engine controller and some concern for direct effects of a strike to the engine nozzle.

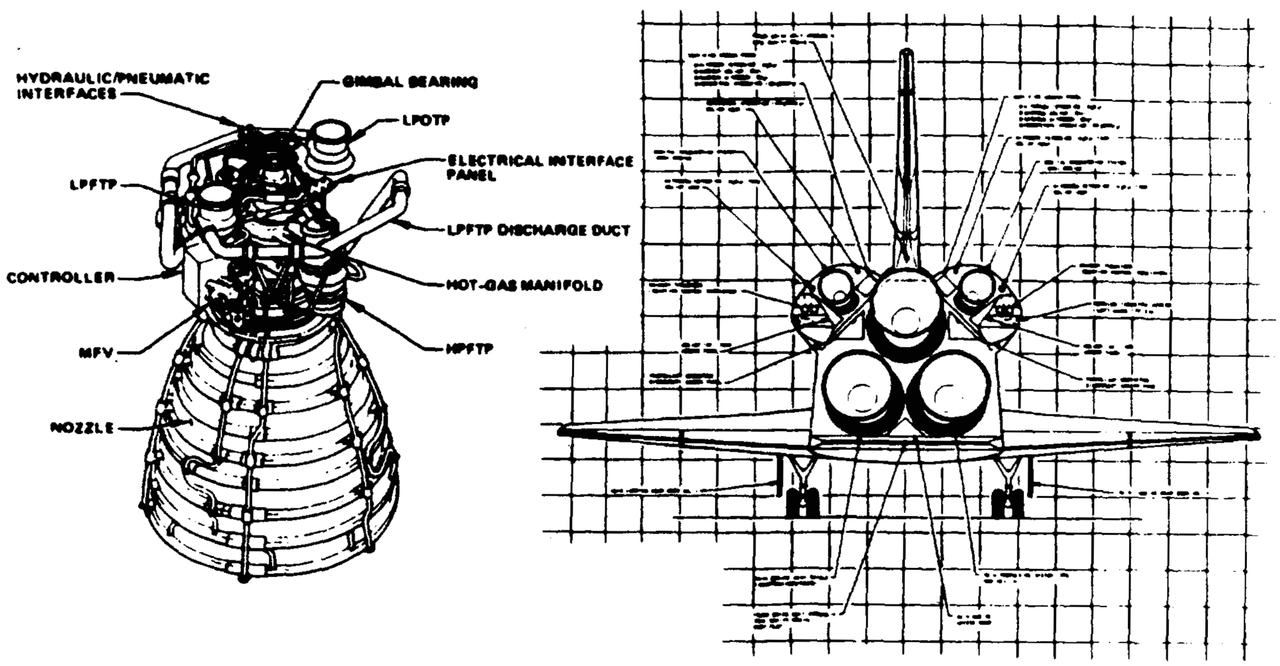


Figure 4. Space Shuttle Main Engine

Main Engine Concerns

A decision was made in 1975 that the main engine was not subject to direct effects of a lightning strike and it was believed that the added cost, weight and schedule of guarding against direct lightning strikes

was not justified. Rationale included consideration that the engine was unlikely to be a primary lightning conductor during boost by virtue of protection afforded by the Orbiter structure and the booster plume and that the engine is not operational during landing and can, if struck by lightning, be repaired.

After the Atlas incident in 1987, it was discovered that certain shielding practices responsible for the Atlas accident were also utilized by the shuttle main engine. A direct lightning strike to the Atlas vehicle altered the core memory in a control unit causing the computer to issue an erroneous yaw command that resulted in destruction of the vehicle. The Space Shuttle Main Engine is a concern because the it contains 40 critical low inertia memory electronic circuits. Several changes were made to the wiring of the engine, e.g., braided cables were added for power, engine interface unit, and sensor interfaces. Shields were terminated on the outside of connector backshells to prevent lightning current from entering the chassis. However, unshielded cable was retained for actuators and this remains a waiver.

The engines are protected from direct lightning strikes by the Orbiter structure with the exception of the nozzles. The engines are not used during decent or landing but then they are more exposed and subject to expensive repair if struck by lightning. The nozzles are heavy steel that should diffuse lightning current away from the lightning attach point without burn through. Tests were conducted on a simulated nozzle section in 1973. The nozzle section withstood 100 kA, 3 ms, discharges provided the air velocity exceeded 40 m/s (90 mph), [3].

<u>SSME Status</u>

Previous analysis qualified the Block I engine controller to a 50 kA strike level derived from an earlier revision of the lightning protection specification. The analysis was for the indirect effects of coupling into cable harnesses by lightning current in the Orbiter skin. The new specification requires the Block II engine controller to be verified by test. Consideration of the direct effects to the nozzle during ascent and descent is also required.

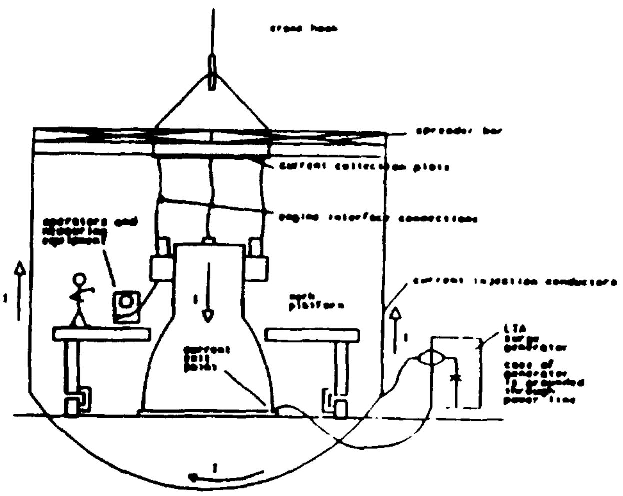


Figure 5. SSME Lightning Protection Test

Cable coupling must be readdressed and two tests are involved. The first series of tests injects relatively low level surge currents (approximately 1000 amps), representative of lightning currents, into the Nozzle as shown in Fig.5. Tests were conducted in December 1990 and January 1991 at Stennis Space Center (SSC) on a flight engine with the engine controller replaced by a dummy controller and flight cables connected. Input and output impedances were simulated and current and voltage

measurements are taken. Measured values are extrapolated to determine the induced voltages and currents should a full amplitude lightning current enter the engine.

A second series of tests is performed with a flight engine controller. Tests are scheduled for April-May 1991. Currents and voltages (induced cable coupling levels determined by previous tests) are injected, by transformer coupling, into the cables of a functioning controller.

SOLID ROCKET BOOSTER

The Solid Rocket Booster (SRB) is illustrated in Fig.6. The length is 46 m (150 ft) and the diameter is 3.7 m (12.17 ft). Major elements of the booster include a nose cap, the solid propellant segments, engine nozzle, and the systems tunnel. Some of the booster segments are joined by factory joints and some are field joints assembled at the KSC launch site. The design for the initial segment joints were a major lightning protection concern because they are apertures that could couple electromagnetic energy into

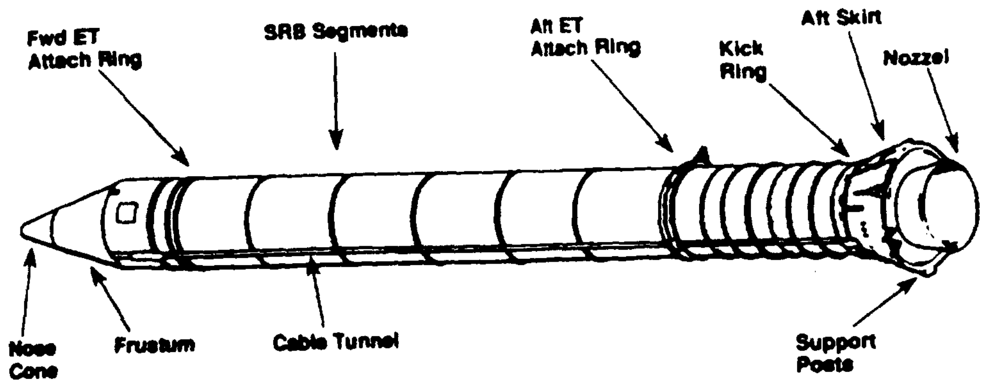


Figure 6. Solid Rocket Booster

the solid propellant. The segment joints for the redesigned booster greatly reduce the potential to couple electric fields into the solid propellant. The steel case, approximately 1.3 cm (one-half inch) thick, eliminates the possibility of puncture due to lightning but does not completely eliminate all consideration for weakening the tank wall. The nose cap and other surface areas susceptible to aerodynamic heating are covered with insulation: typically 0.25 to 0.5 cm (one to two tenth inches) of cork. Vehicle electronics are located in the forward skirt, External Tank attach rings, and in the aft skirt. The major concern for electronics is induced coupling into the systems tunnel wiring that could cause upset or damage to any of 28 criticality I circuits.

Booster Concerns

Considerable activity within the lightning protection and electrostatic discharge community, both military and NASA, resulted from the accidental ignition of a Pershing II motor during assembly operation in West Germany in January, 1985. Electrostatic charging and subsequent internal breakdown within the solid propellent, resulting from removing the first stage motor from its shipping case container, was determined to be the cause. Pershing propellant is more sensitive than the Shuttle solid rocket booster propellant and has a kevlar composite case rather than a steel case as does the booster.

A simplified circuit for testing propellant sensitivity is shown in Fig.7. Test results for the 10 cm long samples indicated the booster propellant to be relatively insensitive at temperatures above -40 $^{\circ}$C (-40°F). The booster propellant, TP-H1148, did not react at -23 to 24°C (-10 to +75°F) temperatures, for

voltages up to 30 kV and therefore the resulting field level of 300 kV/m (30 kV/0.1 m) is considered to be safe for the booster propellant.

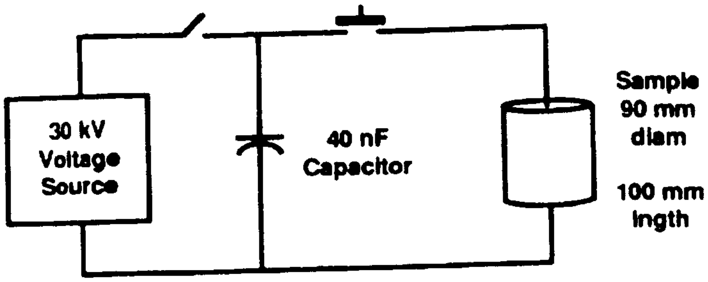


Figure 7. Propellent Sensitivity Test Circuit

Other tests and analyses evaluated induced electric fields from lightning and microwaves under various conditions for the booster [4]. The electric field from lightning current inside the propellant following through booster joints was determined to be 35 kV/m and well below the accepted 300 kV/m safe level. However, the safe level was exceeded when individual booster segments were being shipped from the manufacturing plant in Utah to the Florida launch site. Segments, shipped by rail car, were initially protected by a fiberglass rail car cover and a fiberglass end grain cover over both ends of the segment. Field levels were reduced from 480 kV/m for an unprotected booster segment to 0.06 V/m when the segment was protected by a laminated aluminum rail car and end grain covers. Electric fields resulting from microwaves were well below the safe level (e.g., a worst case microwave environment produced a field of only 80 V/m inside the propellant near the booster joints.)

The indirect effects of lightning were also analyzed and tested. Electrical cabling is routed external to the booster and protected by systems tunnel shown in Fig.8. A lightning strike to the systems tunnel

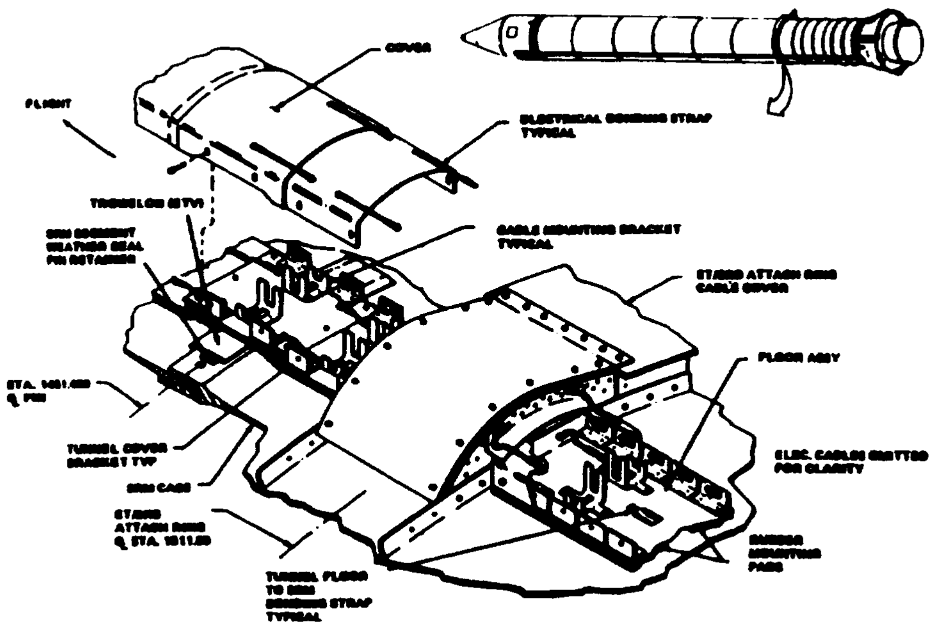


Figure 8. System Tunnel Bond Straps

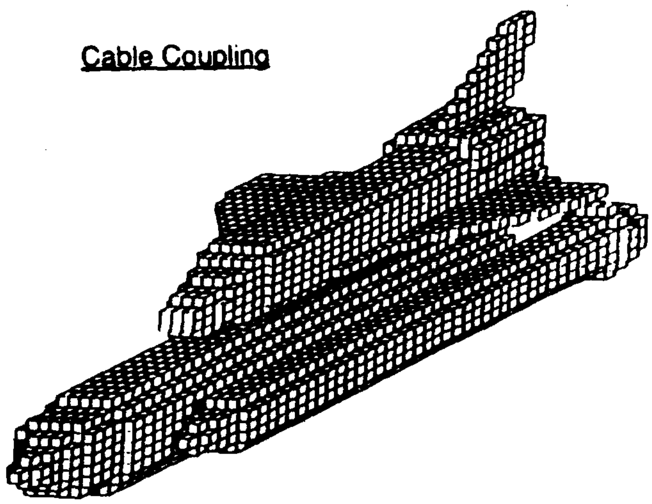
cover must flow to the booster case through bond straps. The bond strap, shown in the figure, is located inside the systems tunnel. One end is bolted to the floor plate and the other end is attached to the steel case with adhesive. Lightning tests were conducted on full size motor segments at Wendover, Utah in 1989 to determine the adequacy of the bond straps [5]. Results from the tests proved that the

internal bond straps were not adequate to survive full lightning currents. Excessive current and voltage was induced into the electrical cables and also caused the internal bond strap to separate at the case end and the loose end sprang straight up from its attachment at the floor. The loose end hit the linear shaped charge contained in the forward systems tunnel. This necessitated sensitivity testing of the linear shaped charge to verify that detonation does not occur.

A retest was conducted in 1990, also at Wendover, Utah. The internal bond strap was replaced by more substantial external cover-to-case bond straps. Cover-to-cover bond straps were also replaced with larger straps and all development flight instrumentation cables were removed. Test results are not available but all bond straps appear to have survived specified current and action interval limits and induced open circuit common mode voltages are reduced from 130 Volts to 30 to 60 Volts based on preliminary inhouse analysis.

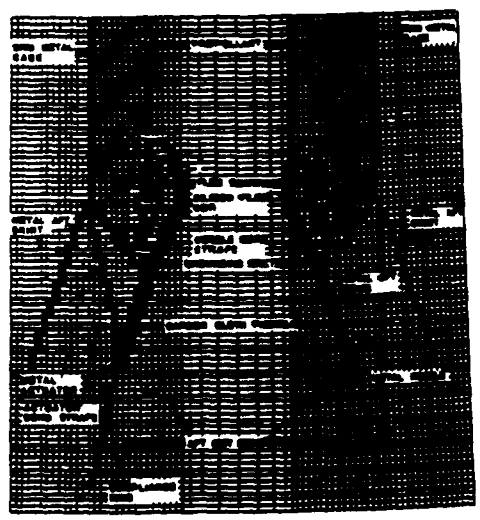
A final lightning current path to be discussed is the lightning detach point. A likely detach point for lightning current is through the booster exhaust plume. However, current must transverse flex gimbals and the nozzle before reaching the exhaust plume. The flex joint is required because the engine must be gimballed to provide thrust vector control. Lightning current must flow through bond straps connecting the booster case to the nozzle. Bolts connecting to the bond straps to the nozzle extend through the nozzle and penetrate the inner carbon nozzle liner. The liner makes electrical contact with the plum. Another lightning current path for reaching the nozzle is though bond straps bypassing the engine actuators. Additional test and analysis sophistication considered the effect of bond strap failures that allow current to loop back toward the booster case near the propellant, and establish high electric fields.

Cable Coupling



Three Dimensional Finite Difference Approach
of Solving Maxwell's Equations
(Electro Magnetic Applications, Inc.)

Electric Fields



Two Dimensional Projection

Figure 9. Numerical Techniques

Testing of the lightning path from the booster case to the inside of the exit cone was performed at Wendover, Utah in 1988, [6]. This report is a noteworthy example of the analytical capability required for lightning protection analysis. Figure 9 is taken from the report to illustrate the numerical method of the finite difference technique of solving Maxwell's equations. The method is implemented by establishing a grid, without undue computer memory requirements, to create a smaller simulated structure capable of representing the pertinent aspects of the rocket motor.

Analysis and test results verified the capability to withstand 200 kA with minor pitting at the screw/carbon liner interface. The electric field strength within the propellant was 17 kV/m when all twelve case to nozzle bond straps and both actuator bond straps were in place. Bond straps were removed sequentially to simulate nozzle and actuator bond strap failures. The field strength increased to the extreme level of 430 kV/m for the limiting case when all nozzle and actuator straps were removed. Recall that the accepted safe level is 300 kV/m.

Solid Rocket Booster Status

Two engineering changes might correct the major lightning protection shortcomings of the booster. One change is being processed to replace the existing nose cap gasket with a conductive gasket. A second change is being evaluated to change the systems cable tunnel bond straps. The latest tests at Wendover, January 1991, evaluated cable coupling into NASA standard initiator circuits for the nozzle severance system. A main lightning path coupon test is contemplated to verify bond joints that must now be verified by analysis or test in accordance with Rev E to NSTS-07636.

CONCLUSION

Lightning protection for the Space Shuttle propulsion elements has been reviewed. Background information on the lightning specification, program history, and element descriptions provided a foundation for discussing design concerns and the status of the present test and analysis efforts. The propulsion elements can no doubt survive certain intensity lightning strikes attaching to less vulnerable vehicle locations during certain mission phases. The NASA lightning specification requires, as it should, that propulsion elements (and the Orbiter) withstand a very severe lightning model under all conditions. The Space Shuttle remains vulnerable in this respect and therefore efforts to improve the lightning protection design for the Space Shuttle continue after more than a decade of flight.

Acknowledgements

To fellow lightning protection engineers at MSFC-SAIL and to the Shuttle propulsion element contractors and subcontractors who have performed the majority of the lightning protection work.

REFERENCES

1. E. J. Lisk, and J. McCardle, Lightning Protection Design Features to Requirements of JSC 07636 Revision C, Lightning Protection Criteria Document, Martin Marietta, 826-2392, dated July 22, 1988.

2. F.A. Plumer and K. E. Crouch, Simulated Lightning Tests on ET Skin Panels, LT-88-480, dated August 1988.

3. Lightning and Transients Research Institute, Simulated Lightning Discharge Current Effects on Space Shuttle Exhaust Nozzle Coolant Tubing, Report No. 563, dated May 1973.

4. Rodney A. Perala, et. al, Electro Magnetic Applications, Inc., Evaluation and Mitigation of Lightning and Microwave Hazards to the SRB Propellant, EMA-87-R-63, dated June 1987.

5. United Technologies USBI, C. O. 191 Lightning Test Final Test Report, USBI-SYS-10-RPT-010, dated December 1989.

6. Morton Thiokol, Analysis of the Systems Tunnel Bond Straps, DFI Cables, and Lightning Test Configuration, TWR-17252, dated March 1990. This report is an introduction to EMA report EMA-88-R-50, dated August 1988.